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WASHINGTON, D. C.

THE INFLUENCE OF THE GROUND (IN THE IMMEDIATE VICINITY OF THE RECEIVING LOCATION) ON THE CALIBRATION AND USE OF VHF FIELD-INTENSITY METERS

BY FRANK M. GREENE

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CONTENTS

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I. INTRODUCTION

As is known, VHF field-intensity measurements will be generally in error if made at antenna heights other than that for which the "antenna constant" was determined when the field-intensity meter was calibrated. A similar error will likewise exist if the ground constants at the site chosen to make measurements are appreciably different from those existing at the time or place of calibration.

Most VHF field-intensity meters at present use a doublet receiving antenna which is usually terminated at its center terminals in a value of impedance roughly equal to its free-space input impedance. The error referred to exists because of the fluctuation of the antenna input impedance with height above ground or with changing ground conditions(1). This results in a corresponding fluctuation in the proportion of the induced voltage which appears across the terminals at the center of the antenna. Consequently the value of the "antenna constant" determined at the time of the calibration is in general no longer the same if the height or ground conditions are altered.

An approximate expression for the input impedance at various heights above a finitely conducting ground may be easily obtained for the case of a horizontal antenna. The ground is assumed to be plane, homogeneous, and with finite values of the relative dielectric constant ϵ_r , and conductivity σ . Once the antenna input impedance is known, the effect of the earth on the "antenna constant" may be determined.

While the solution attempted here is not rigorous, it can be shown to yield the limiting value of the input impedance of a horizontal antenna if its height above ground is increased sufficiently. The results, however, are useful in obtaining approximate values of the input impedance corresponding to antenna heights of a fraction of a wavelength.

Theoretical values of the measurement error referred to above are reasonably well supported by measurement at one particular site for antenna heights down to one-tenth wavelength at 100 Mc. The theoretical

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1.
It is assumed here that the field-intensity meter is calibrated and used at such locations that the distances to the nearest reflecting objects such as trees or buildings are very much greater than the height of the receiving antenna above the ground.

results are based upon the values of the antenna input impedance as determined herein.

In this paper the effect both of changes in ground conditions and of the value of the antenna terminating impedance upon this error are determined. Practical rationalized MKS units are used throughout.

II THEORY

In formulating the following solution, the usual system will be considered comprising a transmitting and receiving antenna at heights h_1 and h_2 respectively above ground. The ground is assumed to be plane, homogeneous, and of infinite extent, having finite values of relative dielectric constant ϵ_r and conductivity σ. While the method is applicable to horizontal antennas of any length, the results will be evaluated only for the case of parallel horizontal half-wave dipoles. Their locations and the geometry involved are shown in Fig. 1.

In addition to the direct and ground-reflected rays along R_1 and R_2 respectively, a ray will be considered which leaves each antenna and is reflected at normal incidence from the ground back to the antenna.

(a) Perfectly Conducting Ground

Perfectly conducting ground will be considered first. Its effect may be simulated in the usual manner by postulating the image antennas (2) and (4), each located a distance below the perfect reflecting plane equal to the height of the actual antenna. The two antennas and their images may be treated as four coupled antennas. The resulting voltage-current relationship will have exactly the same form as would exist in a linear four-mesh network. For this case the resulting four equations reduce to the following two[2]:

$$\begin{aligned} V &= I_1 (Z_{11} - Z_{12}) + I_3 (Z_{13} - Z_{14}) \\ 0 &= I_1 (Z_{31} - Z_{32}) + I_3 (Z_{33} - Z_{34}) \end{aligned} \qquad \text{. . . . . (1)}$$

V = impressed emf at the center of the transmitting antenna.

I_1, I_2, I_3, and I_4 are the respective currents at the centers of the four antennas.

Z_{11} and Z_{33} are the free-space self-impedances respectively of the transmitting and receiving antennas referred to the center terminals.

$$Z_{mn} = Z_{nm} = \frac{-V_{mn}}{I_n} \qquad \text{. . . . . (2)}$$

2. Karr, P.R., The influence of the ground upon the voltage induced in a receiving antenna. Report OD-2-348R (NBS) July 23, 1947.

Z_{mn} = mutual impedance between antennas m and n.

V_{mn} = voltage induced in antenna m (referred to the center terminals) by the current, I_n, at the center of antenna n.

(b) Finitely Conducting Ground

In considering the case involving a finite earth, the equations for meshes (2) and (4) of the previous system become meaningless. However, by benefit of analogy with equations (1) and with the aid of experimental evidence one may write a similar set of equations involving antennas (1) and (3) and the ground which under certain conditions describe this transmission system to a first approximation at least. The equations are

$$\begin{aligned} V &= I_1 (Z_{11} + \Gamma 1\, Z_{12}) + I_3 (Z_{13} + \Gamma 2\, Z_{14}) \\ 0 &= I_1 (Z_{31} + \Gamma 2\, Z_{32}) + I_3 (Z_{33} + \Gamma 1\, Z_{34}) \end{aligned} \quad \ldots\ldots\ldots(3)$$

where

$\Gamma 1 = \rho_1 e^{-j\phi_1}$ = complex plane-wave reflection coefficient for normal incidence.

$\Gamma 2 = \rho_2 e^{-j\phi_2}$ = complex plane-wave reflection coefficient (horizontal polarization) for the angle $\psi = \tan^{-1} \dfrac{h_1 + h_2}{d}$ made by the principal ground-reflected ray (along R_2) with the earth.

$\Gamma 2$ may be expressed in terms of the angle ψ and a complex dielectric constant ϵ_o as follows (3) (for horizontal polarization).

$$\Gamma 2 = \frac{\sin\psi - \sqrt{\epsilon_o - \cos^2\psi}}{\sin\psi + \sqrt{\epsilon_o - \cos^2\psi}} \quad \ldots\ldots\ldots(4)$$

where $\epsilon_o = \epsilon_r \left(1 - j\dfrac{\sigma}{\epsilon\omega}\right)$

$= \epsilon_r - j\, 60\lambda\sigma$

ϵ_r = relative dielectric constant of the ground (referred to free-space as unity).

$\epsilon = \epsilon_v \epsilon_r$, where ϵ_v is the permittivity of evacuated free-space.

$\epsilon_v \cong \dfrac{1}{36\pi} \times 10^{-9}$ farads/meter

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3.
Stratton, J.A., Electromagnetic Theory, p 493, McGraw-Hill Book Co., New York, 1941.

σ = ground conductivity in mhos/meter

ω = $2\pi f$

λ = wavelength in meters

Equations (3) will reduce to (1) if the ground conductivity σ is allowed to increase without limit, since in this case $\Gamma_1 = \Gamma_2 = -1$ for all angles of incidence as can be seen from equation (4).

(c) Evaluating the Self and Mutual Impedances

Before practical use can be made of equations (3) the various self and mutual impedances must be evaluated. Schelkunoff[4] has determined the free-space input impedance of cylindrical antennas in general. Values may be obtained graphically from Figs. 11.21 and 11.22 of this reference for antennas of several length-to-diameter ratios. A value of 73.2 + j 42.5 (ohms) may be used if desired corresponding to a thin $\lambda/2$ dipole in free-space, without substantially affecting the resulting value of the measurement error. Carter [5] has evaluated the mutual impedance between antennas of various configurations. For the case of parallel half-wave dipoles in free-space the mutual impedance is

$$Z = 30\left\{ 2\,Ei\,(-jkR) - Ei\left[-jk\left(\sqrt{R^2 + \ell^2} + \ell\right)\right] - Ei\left[-jk\left(\sqrt{R^2 + \ell^2} - \ell\right)\right]\right\} \text{ ohms} \quad \ldots\ldots\ldots (5)$$

where ℓ = antenna length in meters.

R = distance between antennas in meters.

$Ei(-jx) = Ci(x) - j\,Si(x)$

$k = 2\pi/\lambda$

$j = \sqrt{-1}$

Values of (5) are shown plotted in Figs. 11 and 12 of reference (5) for spacings from 0 to 7.5 wavelengths.

It is possible to derive a more simple expression than (5), valid for distances of separation in excess of about 2λ. At this distance from an antenna only the radiation component of the electric field-intensity usually need be considered. For a half-wave dipole in free-space, oriented normal to a line from its center to the observer, the field-intensity is given by(5)

4. Schelkunoff, S.A., Electromagnetic Waves, pp 441-479, D. Van Nostrand Co., New York, 1943.

5. Carter, P.S., Circuit relations in radiating systems and applications to antenna problems, Proc. I.R.E., 20, pp 1004-1041, June 1932.

$$E \cong -j \frac{60 I}{R} e^{-j\frac{2\pi R}{\lambda}} \quad \text{(volts/meter)} \qquad \ldots\ldots (6)$$

where

R = distance in meters.

I = current in amperes at the center of the antenna.

The voltage (referred to the center terminals) induced in a half-wave dipole placed in the field given by (6) and oriented parallel to the transmitting antenna is

$$V \cong E l_H \cong -j \frac{60 \lambda I}{\pi R} e^{-j\frac{2\pi R}{\lambda}} \text{ (volts)} \qquad \ldots\ldots (7)$$

where l_H = effective length of the dipole in meters.

$l_H \cong \lambda/\pi$ meters for a half-wave dipole assuming sinusoidal current distribution.

From (7) and (2) the mutual impedance between the two parallel half-wave dipole antennas is

$$Z = \frac{-V}{I} = j \frac{60\lambda}{\pi R} e^{-j\frac{2\pi R}{\lambda}} \quad \text{(ohms)} \qquad \ldots\ldots (8)$$

It can be shown[6] that the value of mutual-impedance given by (5) approaches that given by (8) for sufficiently large values of the distance of separation, R. In fact for separations in excess of about 2 λ the value of mutual impedance given by (8) is sufficiently accurate for most purposes and will cause less than 0.1 percent error in the final results in which we are interested here. For smaller values of separation than 2 λ between the antennas, equation (5) or figures 11 and 12 of reference (5) must be used to evaluate the mutual impedance.

III RELATIONS EXISTING IN THE RECEIVING ANTENNA

(a) Antenna Current

Equations (3) may now be solved for the current I_3 at the center of the receiving antenna. The problem will be simplified if it is assumed that the distance between transmitting and receiving antennas is sufficiently large that the presence of the receiving antenna does not measurably affect the current flowing in the transmitting antenna.

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6. Affanasiev, Kosmo J., Simplifications in the consideration of mutual effects between half-wave dipoles. Proc. I.R.E., 34, pp 635-638, September 1946.

This is usually the case in practice and the assumption is certainly justified if the spacing is at least several wavelengths. In this case the current in the receiving antenna terminated at its center in a load impedance Z_L is, from (3),

$$I_3 = - \frac{(Z_{31} + \Gamma_2 Z_{32}) I_1}{Z_L + Z_{33} + \Gamma_1 Z_{34}} \qquad \ldots\ldots (9)$$

(b) The Input Impedance

The numerator of (9) is the induced emf in the receiving antenna, and the denominator is the input impedance (in the presence of the ground) plus the terminating impedance Z_L connected at the center, the input impedance being

$$Z_i = Z_{33} + \Gamma_1 Z_{34} \qquad \ldots\ldots (10)$$

The effect of the ground in the immediate vicinity of the receiving antenna is accounted for by the second term on the right of (10), $\Gamma_1 Z_{34}$. Z_{34} is the mutual impedance that would exist between the receiving antenna and its image if the ground were perfectly conducting, and is given by (5) or (8) upon substituting $R = 2h_2$. Γ_1 is of course the actual reflection coefficient of the ground for normal incidence obtained from (4) by placing $\psi = \frac{\pi}{2}$ which gives

$$\Gamma_1 = \frac{1 - \sqrt{\epsilon_r(1 - j\frac{\sigma}{\epsilon\omega})}}{1 + \sqrt{\epsilon_r(1 - j\frac{\sigma}{\epsilon\omega})}} \qquad \ldots\ldots (11)$$

Values of the magnitude of (11) are shown plotted in Fig. 2 vs ϵ_r for low loss dielectrics, $\left(\frac{\sigma}{\epsilon\omega} \ll 1\right)$. Many types of ground may be treated as low-loss dielectrics over a large portion of the VHF band as far as their reflecting properties are concerned. This is particularly true at the higher frequencies above 50 or 75 Mc.

(c) Voltage Relations

The terminal voltage of the receiving antenna terminated in an impedance Z_L is, from (9)

$$V_L = - \frac{(Z_{31} + \Gamma_2 Z_{32}) Z_L I_1}{(Z_L + Z_{33} + \Gamma_1 Z_{34})} \qquad \ldots\ldots (12)$$

and the open-circuit voltage is, letting $Z_L \rightarrow \infty$

$$V_{oc} = -(Z_{31} + \Gamma_2 Z_{32}) I_1 \qquad \ldots\ldots (13)$$

If the receiving antenna is sufficiently high above the ground, Z_{34} may be considered negligible compared to $(Z_L + Z_{33})$ in which case the terminal voltage will be, from (12),

$$V_L = \frac{-(Z_{31} + \Gamma_2 Z_{32})\, Z_L\, I_1}{Z_L + Z_{33}} \quad \ldots\ldots (14)$$

The true value of the electric component of field-intensity at any antenna height, h_2, above the ground is, from (7) and (13)

$$E_t = \frac{V_{oc}}{\ell_H} = -\frac{(Z_{31} + \Gamma_2 Z_{32})\, I_1}{\ell_H} \quad \ldots\ldots (15)$$

The value of field-intensity that would be indicated by a field-intensity meter previously calibrated in the presence of the ground is, from (12),

$$E_i = KV_L = -\frac{K(Z_{31} + \Gamma_2 Z_{32})\, Z_L\, I_1}{(Z_L + Z_{33} + \Gamma_1 Z_{34})} \quad \ldots\ldots (16)$$

K may be defined as the "antenna constant" and may be evaluated at any desired height of the receiving antenna. If a height h_2 is chosen such that $Z_{34} \ll (Z_L + Z_{33})$. K might be then termed the "free-space antenna constant" and in such a case its value would be

$$K \cong \frac{1}{\ell_H}\left(\frac{Z_L + Z_{33}}{Z_L}\right) \quad \ldots\ldots (17)$$

since $E_t \cong E_i$ at this height.

IV EVALUATION OF THE MEASUREMENT ERROR

The percentage difference between the true value of field-intensity existing at some antenna height h_2, and that indicated by a field-intensity meter with a previously determined "antenna constant" is

$$\delta = \left(\left|\frac{E_i}{E_t}\right| - 1\right) \times 100 \text{ (percent)} \quad \ldots\ldots (18)$$

In the case in which the "antenna constant" was determined at a sufficient antenna height that K may be considered to have a "free-space" value, the above difference, or measurement error, may be obtained by substituting (15), (16), and (17 in (18) giving

$$\delta = \left(\left|\frac{Z_L + Z_{33}}{Z_L + Z_{33} + \Gamma_1 Z_{34}}\right| - 1\right) \times 100 \text{ (percent)} \quad \ldots\ldots (19)$$

Z_L = load impedance connected to the center terminals of the receiving antenna

Z_{33} = input impedance (in free space) of the receiving antenna. Z_{33} may be evaluated from Figs. 11.21 and 11.22 of reference (4), or if desired may be taken as $73.2 + j42.5$ (ohms) corresponding to a thin $\lambda/2$ dipole in free-space, without substantially affecting the resulting value of the measurement error.

Z_{34} may be evaluated from equation (5), or from Figs. 11 and 12 of reference (5). For heights of the receiving antenna $h_2 \geq \lambda$, Z_{34} may be evaluated from equation (8), placing $R = 2h_2$. This gives

$$Z_{34} = j\,\frac{30\lambda}{\pi h_2}\,e^{-j\frac{4\pi h_2}{\lambda}} \text{ (ohms)} \qquad \ldots\ldots (20)$$

Γ_1 = plane-wave reflection coefficient for normal incidence. Γ_1 may be evaluated from equation (11), or in the case of low-loss dielectrics, from Fig. 2.

V DISCUSSION OF RESULTS

The measurement error to be discussed is that existing in a field-intensity meter whose "antenna constant" was determined under "free-space" conditions. This error or difference (as calculated) is given by (19) and is shown in Figs. 3, 4, and 5 vs h_2/λ for various values of the parameters Γ_1 and Z_L. Measured values of the error determined at one particular site ($f = 100.0$ Mc) are also shown in Fig. 5.

Fig. 3 shows the effect of changes in the ground constants on the measurement error calculated for an antenna terminated in an impedance $Z_L = 73 + j0$ ohms. The self-impedance of the antenna was assumed to be $73.2 + j\,42.5$ ohms. Curves are shown for (a) $\sigma = \infty$, (b) $\epsilon_r = 9$, (c) $\epsilon_r = 15$, and (d) $\epsilon_r = 30$. Low-loss dielectrics were assumed in the last three cases.

The high and low values of the relative dielectric constant chosen represent the approximate extremes measured at one particular site ($f = 100.0$ Mc) during the summer of 1948. The value, $\epsilon_r = 15$, is usually assigned to "average" ground along with a value of conductivity $\sigma = 5\text{x}10^{-3}$ mhos/meter. This value of conductivity can be ignored, at least for frequencies above 50 Mc (as far as its effect on the reflection coefficient ($\psi = \pi/2$) is concerned).

Apparently the usual changes in the ground constants experienced (due to changing moisture content) have but little effect upon the measurement error as presented here. The total variation from "average ground" conditions ($\epsilon_r = 15$) does not exceed 1.5 percent except for values of $h_2/\lambda < 0.15$.

As shown by Fig. 3, a field-intensity meter ($Z_L = 73\,\Omega$) calibrated under "free-space" conditions may indicate values of field-intensity which are in error by as much as 10 percent for values of h_2/λ near 0.3, and 7.5 percent for values of h_2/λ near 0.6. If this error is to be held to values less than 5 percent, antenna heights greater than about 0.65 wavelength should be used for field-intensity measurements under these conditions.

It is somewhat doubtful at the present state of the art just what maximum values of measurement error of this type should be permitted. One method of reducing the error, obviously, is to increase the value of the antenna terminating impedance, Z_L.

Fig. 4 shows the calculated measurement error vs h_2/λ for values of $Z_L = 73$, 150, and 300 ohms all for "average ground", $\epsilon_r = 15$, ($\sigma = 0$). For the case of $Z_L = 73$ ohms, the error does not exceed 10 percent for heights of the receiving antenna in excess of 0.15 wavelengths. If Z_L is increased to 150, and 300 ohms this error is reduced to 7 and 4 percent respectively.

Fig. 5 shows the computed measurement error for both a $\lambda/2$ dipole and a self-resonant dipole as well as measured values for the latter case. In the case of the $\lambda/2$ dipole, $Z_{33} = 73.2 + j\,42.5$ ohms and $Z_L = 73 + j0$ ohms. For the self-resonant dipole, $Z_{33} = 65 + j\,0$ ohms and $Z_L = 62 + j0$ ohms.

The latter values were chosen as representing the approximate impedances of the self-resonant antenna actually used for obtaining the measured points of Fig. 5. The terminating impedance, $Z_L = 62$ ohms, was the closest value to 65 ohms available at the time the measurements were made. As might be expected there is no substantial difference between the calculated values of the measurement error for the full $\frac{\lambda}{2}$ dipole and for the self-resonant dipole. The measured points support the theory reasonably well. The difference does not exceed 3 percent for antenna heights above 0.1 wavelength.

The measured values were obtained from the data presented in Fig. 6. Curves are shown of the receiving antenna terminal voltage vs height h_2 in meters for the antenna both "open circuited" and terminated in $Z_L = 62 + j0$ ohms. From these curves it was possible to obtain an approximate value for the "free-space" antenna "transfer-constant", $K' = V'_L/V'_{oc}$. The "error" plotted in the upper curve is actually the percentage change in K' vs h_2 in meters, but is identical in value to the error as defined by (18).

For the "open circuited" condition referred to above the receiving-antenna was actually terminated in a special balanced voltmeter of the silicon crystal-rectifier type. This crystal rectifier, together with the balanced RC network used to take off the dc output-voltage, presented

a resistance of approximately 4000 ohms in shunt with 0.75 micromicrofarads across the gap at the center of the antenna. This accounts for the slight oscillation of the points around the averaging curve, but introduced an error of less than one percent in the final results, as the "shunting" was present during both the "open circuited" and terminated runs.

VI CONCLUSIONS

An approximate method has been presented for determining the effect of finitely conducting ground beneath a horizontal receiving dipole on the value of the "antenna constant" as used for measuring VHF field-intensity. Three variables are mainly involved in this effect: (a) the antenna height, h_2; (b) the ground constants ϵ_r and σ; (c) the antenna terminating impedance Z_L.

Changes in antenna height probably have the greatest effect on the "antenna constant," as can be seen from Fig. 3, and are of primary concern here. Normal variations in the ground constants encountered in practice apparently have only a minor effect. Under most conditions and to within the probable accuracy of this method, these variations can probably be neglected.

This error(7) in measurement caused by the ground-effect may be reduced by increasing the value of Z_L. The error vs height is shown in Fig. 4 for three values of Z_L viz 73, 150, and 300 ohms. The error approaches zero as Z_L approaches infinity.

In Fig. 5, measured values of the error are compared with theoretical values calculated as previously described. The agreement is reasonably good for antenna heights above 0.1 wavelength.

In view of the approximations involved it is felt that the curves shown in figures 3, 4, and 5 probably should not be used for actually applying corrections to field-intensity measurements. Rather they might be used to estimate the maximum possible error (due to ground effect) existing in measurements made below a given antenna height.

Fig. 3 shows the variations in the error with antenna height occurring over perfectly conducting ground. The error is appreciably larger in this case than for finitely conducting ground. This would seem to indicate the inadvisability of using or calibrating a VHF field-intensity meter over a perfectly conducting plane unless the antenna heights were carefully chosen so as to result in a low value of error.

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(7) The error, as previously defined, is the percentage-difference between the true value of field-intensity existing at a given antenna height h_2, and that indicated by a field-intensity meter whose "antenna constant" was determined under "free-space conditions.

VII LIST OF CAPTIONS

Fig. 1 - Ray-path diagram showing: (a) direct ray along R_1; (b) ground-reflected ray along R_2; (c) rays from both transmitting and receiving antennas reflected at normal incidence from the ground back to the antenna. Heights of the transmitting and receiving antennas are h_1 and h_2, respectively and d is the horizontal distance of separation.

Fig. 2 - Magnitude, ρ, of the plane-wave reflection coefficient (at normal incidence) vs ϵ_r, the relative dielectric constant. Low loss dielectrics are assumed $\left(\frac{\sigma}{\epsilon\omega} \ll 1\right)$.

Fig. 3 - Calculated percentage difference vs receiving antenna height h_2 in wavelengths (between the true value of field-intensity, E_t, and the value, E_i, indicated by a field-intensity meter with a previously determined "free space" value of "antenna constant"). Curves are shown for four values of ground constants: (a) $\sigma = \infty$; (b) $\epsilon_r = 9$; (c) $\epsilon_r = 15$; and (d) $\epsilon_r = 30$ (for low-loss dielectrics $\frac{\sigma}{\epsilon\omega} \ll 1$. Antenna length $l = \frac{\lambda}{2}$. The free-space antenna input impedance is taken as $Z_{33} = 73.2 + j\,42.5$, and the terminating impedance $Z_L = 73 + j0$ ohms.

Fig. 4 - Calculated percentage difference in field-intensity vs receiving antenna-height h_2 in wavelengths for three values of antenna terminating impedance, $Z_L = 73$, 150, and 300 ohms, over average ground $\epsilon_r = 15$, $\frac{\sigma}{\epsilon\omega} \ll 1$. $l = \frac{\lambda}{2}$, $Z_{33} = 73.2 + j\,42.5$.

Fig. 5 - Calculated percentage difference in field-intensity vs receiving antenna height h_2 in wavelengths over average ground, $\epsilon_r = 15$, $\frac{\sigma}{\epsilon\omega} \ll 1$, for both a half-wavelength dipole and a self-resonant dipole $l \cong \frac{\lambda}{2}$. The measured points were determined at 100.0 Mc and were obtained from the data presented in Fig. 6.

Fig. 6 - Measured values of receiving antenna terminal-voltage vs height in meters (over ground with a measured relative dielectric constant $\epsilon_r \cong 15$, $\frac{\sigma}{\epsilon\omega} \ll 1$) for (a) antenna "open circuited," and (b) antenna terminated in $Z_L = 62 + j0$ ohms. The measured percentage-difference was obtained from the relation $(K'V_{oc}/V_L - 1) \times 100$, where $K' = V_L'/V_{oc}$ is the "free-space" antenna transfer-constant as estimated from the data (f = 100.0 Mc).

Fig. 7 - View of the various pieces of equipment used in obtaining the measured data of Fig. 6. In the background is shown the ladder-mast and carriage for the receiving dipole. The location is the Beltsville (Maryland) Airport.

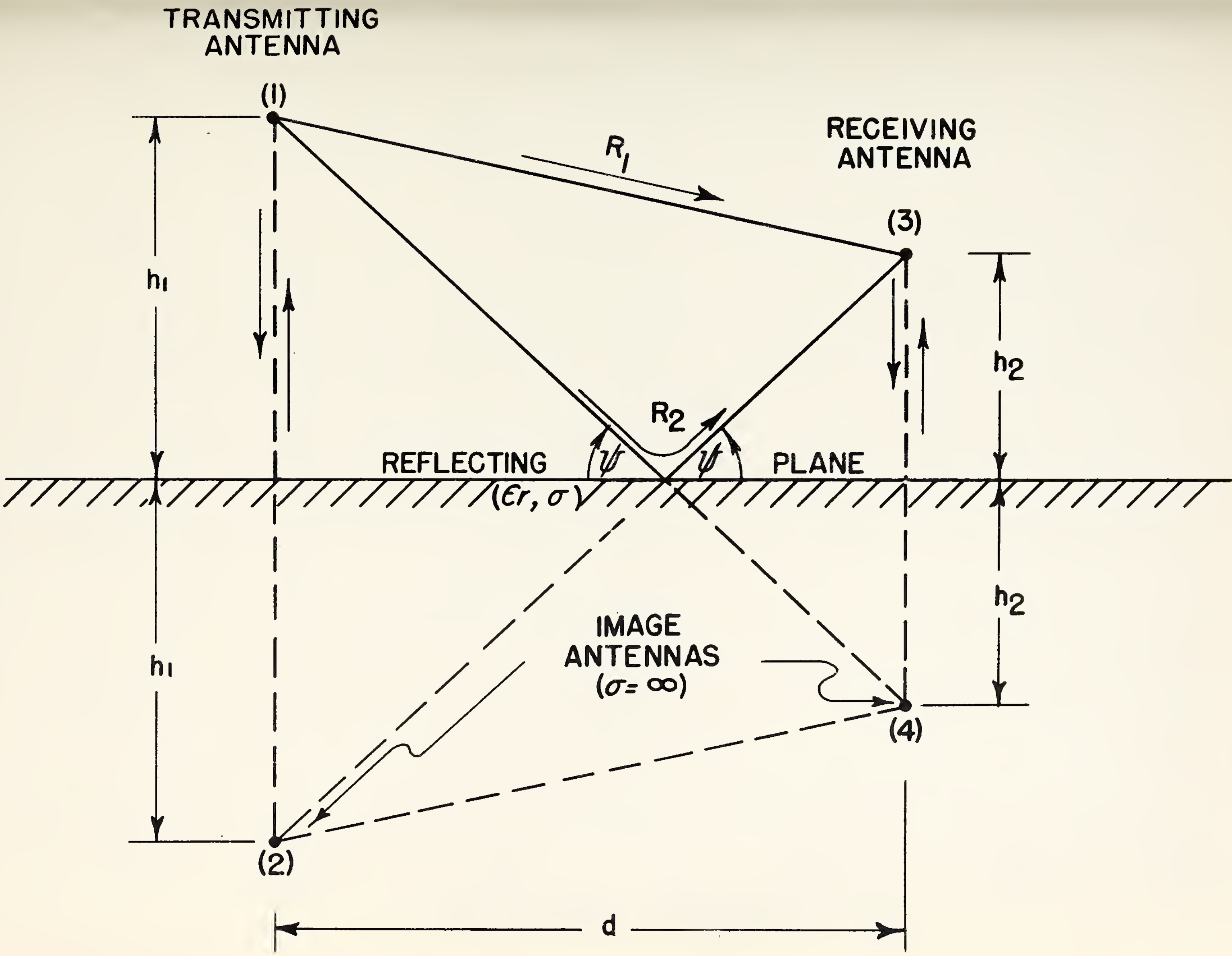

TRANSMITTING
ANTENNA
(1)
RECEIVING
ANTENNA
(3)
R_1
R_2
h_1
h_1
h_2
h_2
ψ
ψ
REFLECTING
PLANE
$(\epsilon r, \sigma)$
IMAGE
ANTENNAS
$(\sigma = \infty)$
(2)
(4)
d

FIG. 1

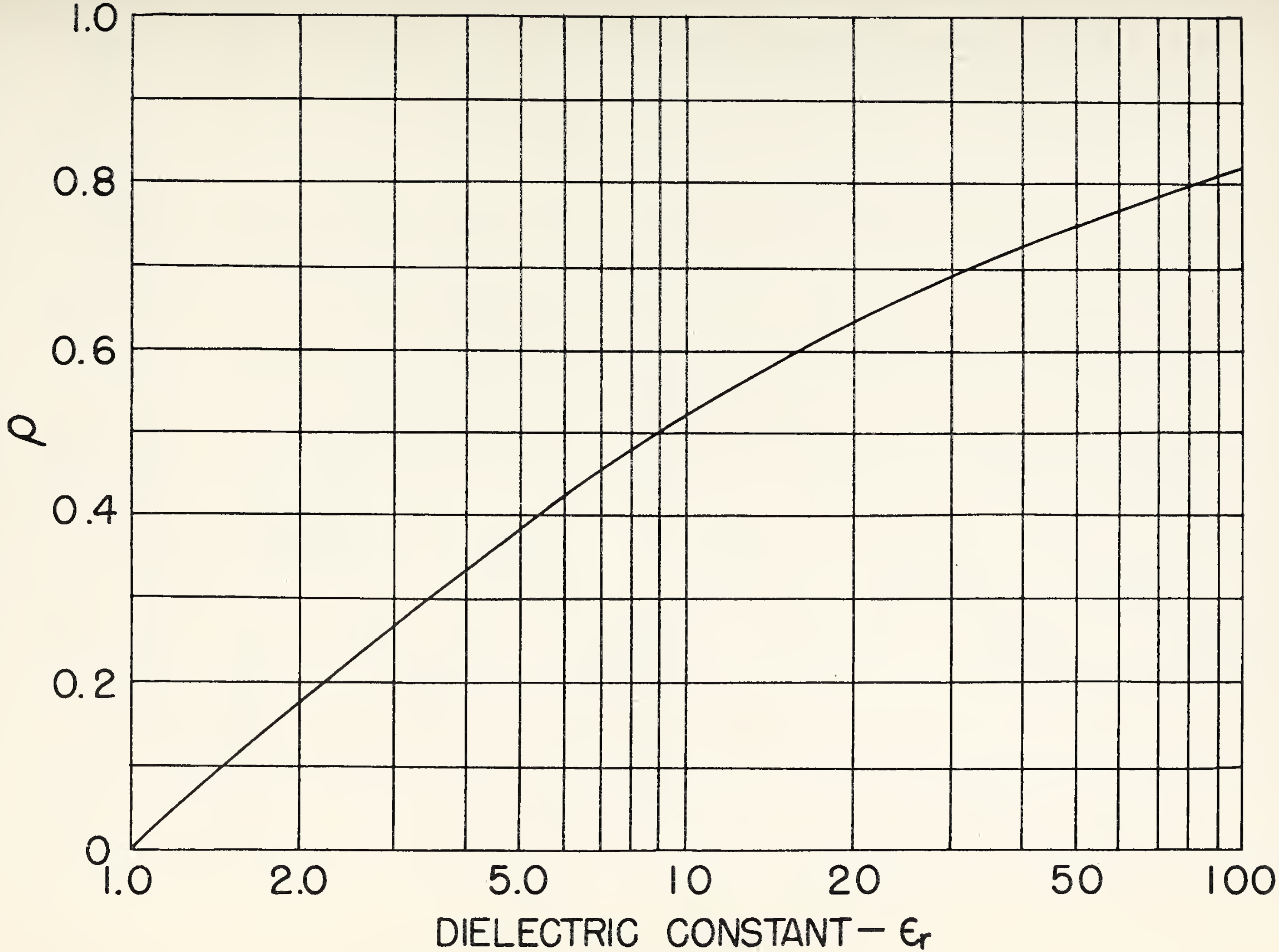

1.0
0.8
0.6
0.4
0.2
0
ρ
1.0
2.0
5.0
10
20
50
100
DIELECTRIC CONSTANT — ϵ_r

FIG. 2

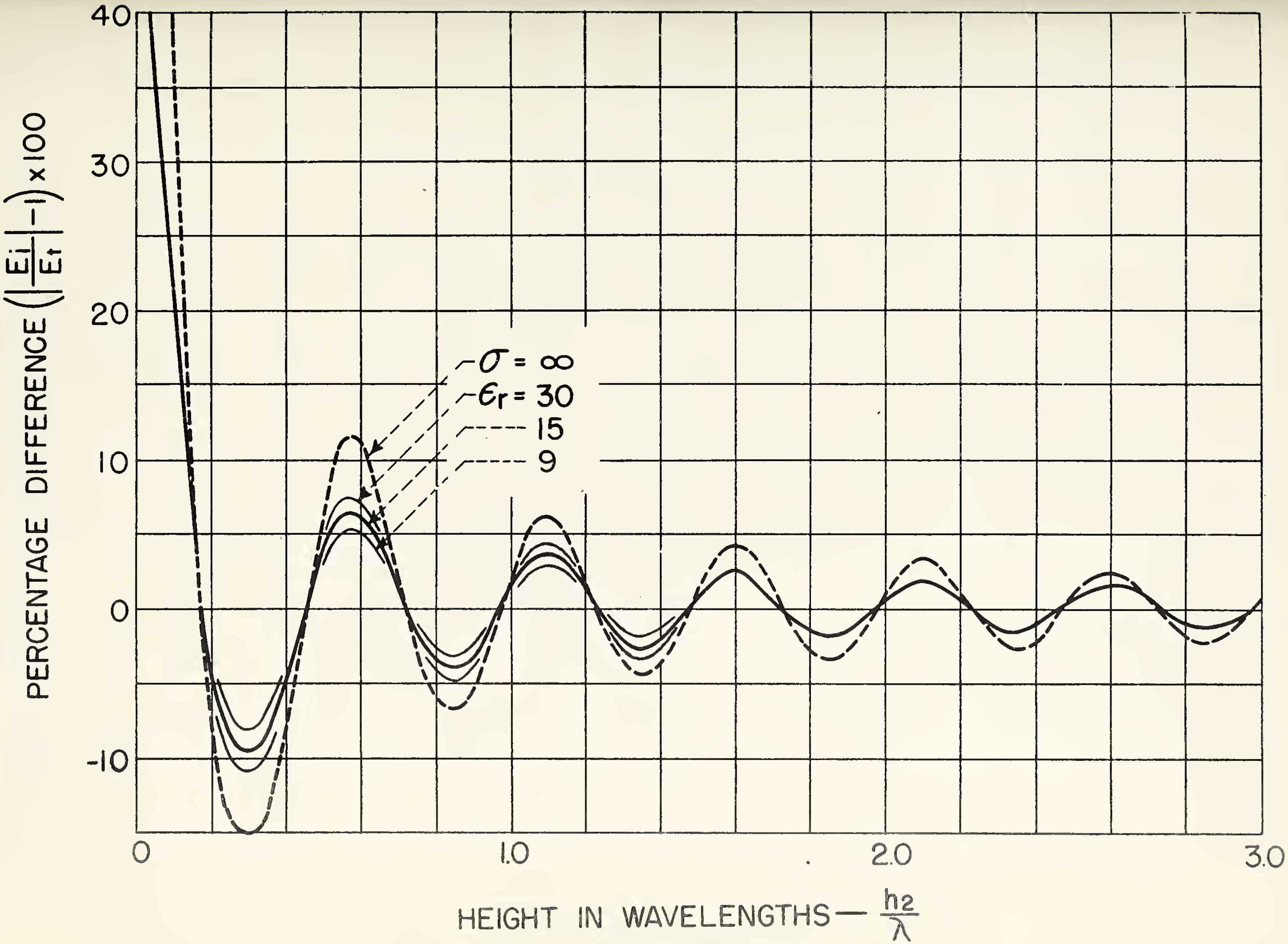

40
30
20
10
0
-10
0
1.0
2.0
3.0
PERCENTAGE DIFFERENCE $\left(\left|\frac{E_i}{E_t}\right|-1\right)\times 100$
$\sigma = \infty$
$\epsilon_r = 30$
15
9
HEIGHT IN WAVELENGTHS — $\frac{h_2}{\lambda}$

FIG. 3

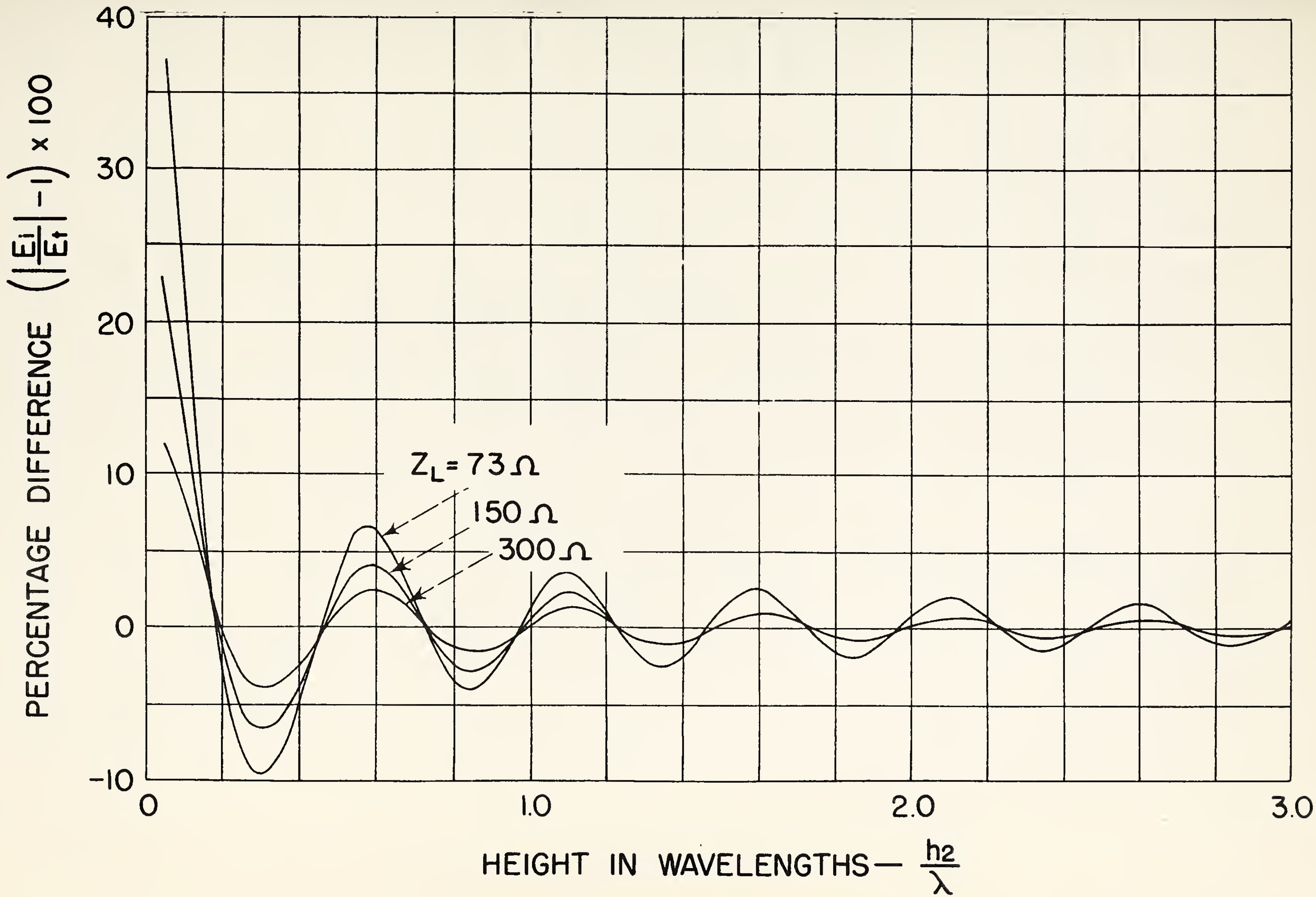

PERCENTAGE DIFFERENCE $\left(\left|\frac{E_i}{E_t}\right| - 1\right) \times 100$
40
30
20
10
0
-10
0
1.0
2.0
3.0
HEIGHT IN WAVELENGTHS— $\frac{h_2}{\lambda}$
$Z_L = 73\,\Omega$
150 Ω
300 Ω

FIG. 4

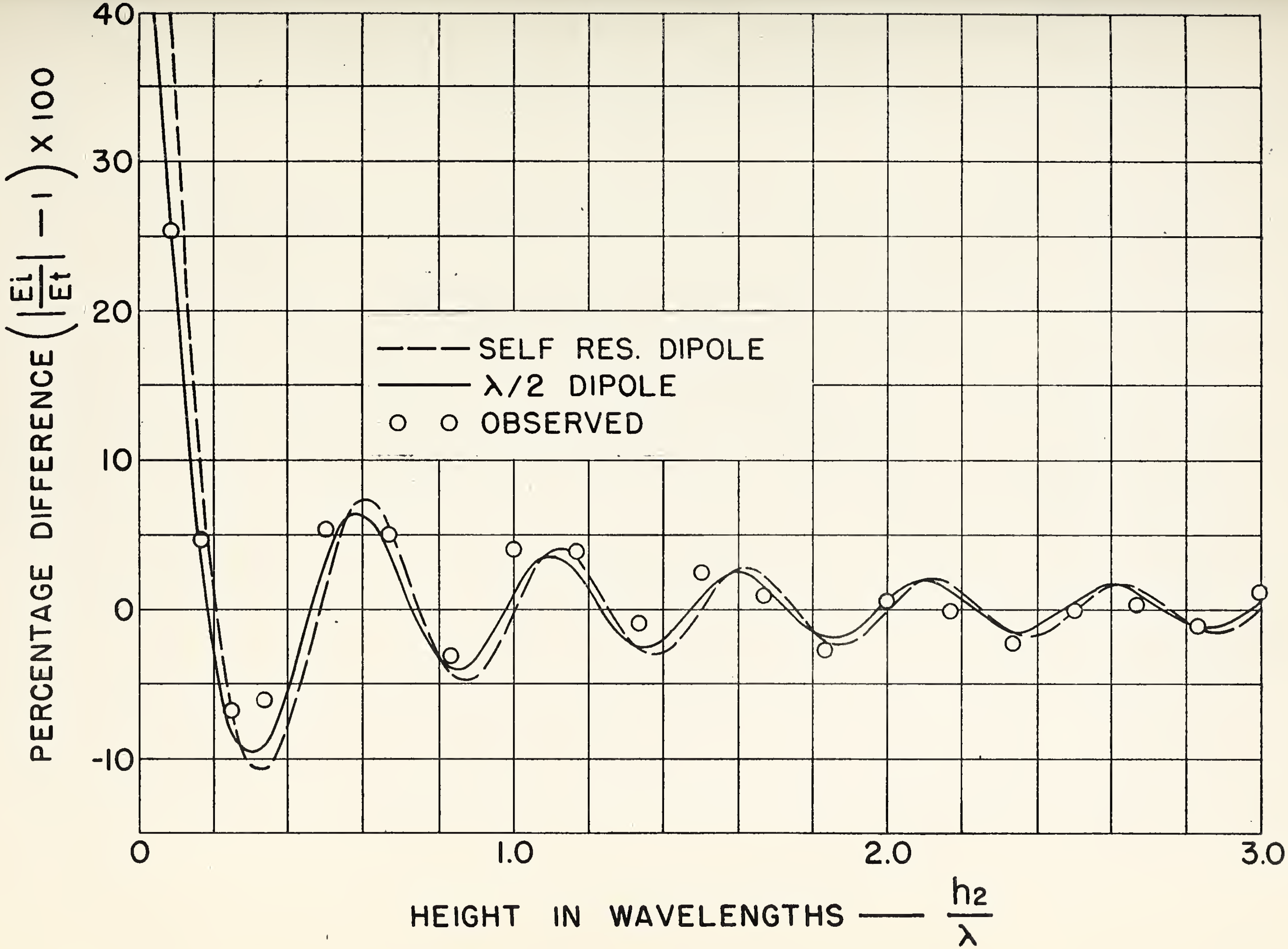
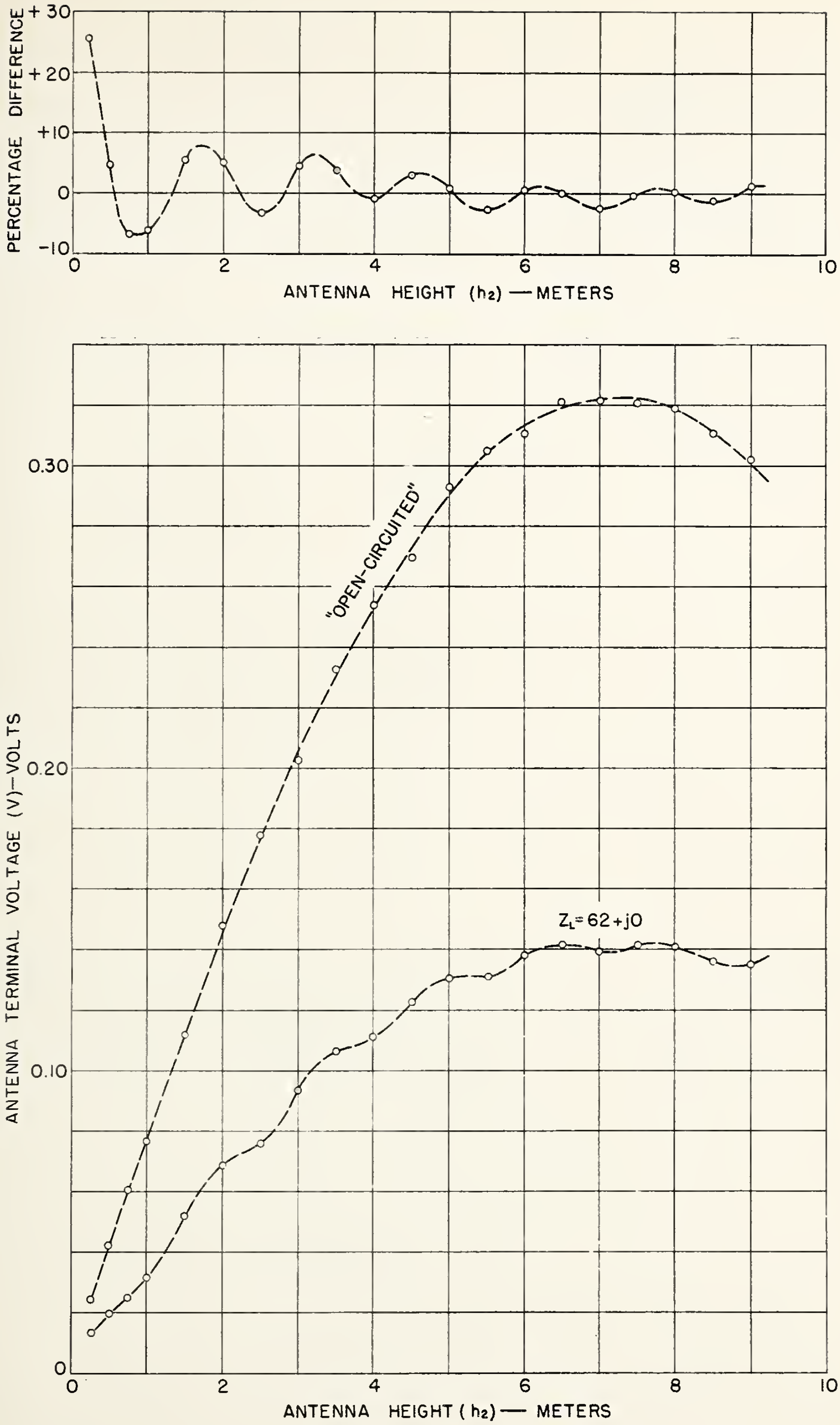

40
30
20
10
0
-10
PERCENTAGE DIFFERENCE $\left(\left|\frac{E_i}{E_t}\right| - 1\right) \times 100$
SELF RES. DIPOLE
λ/2 DIPOLE
OBSERVED
0
1.0
2.0
3.0
HEIGHT IN WAVELENGTHS —— $\frac{h_2}{\lambda}$

FIG. 5



PERCENTAGE DIFFERENCE
+30
+20
+10
0
-10
0
2
4
6
8
10
ANTENNA HEIGHT (h2) — METERS
ANTENNA TERMINAL VOLTAGE (V) — VOLTS
0.30
0.20
0.10
0
"OPEN-CIRCUITED"
ZL = 62 + j0
ANTENNA HEIGHT (h2) — METERS

FIG. 6

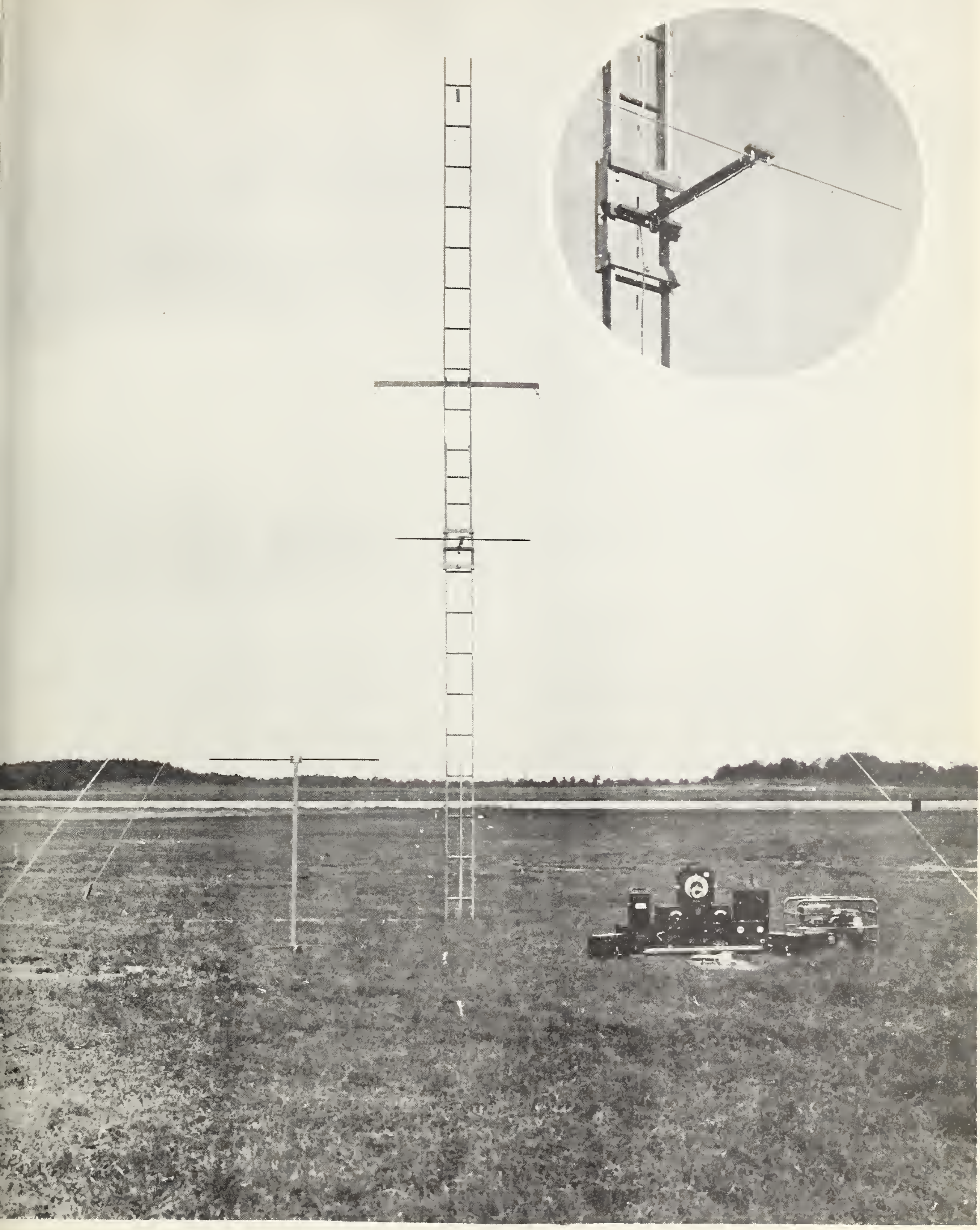


FIG. 7